Lightning Protection for Rotating Machines

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Synopsis: The high monetary value and low insulation levels of rotating machines make it necessary to employ special protection. A rotating machine can be conceived as a transmission line with distributed constants, the essential difference being that the machine winding is wound back on itself in the form of turns, which may permit high voltage across the turn-to-turn insulation. The installation of special arresters with low and consistent spark-over characteristics will limit satisfactorily the maximum voltage that can appear across the terminals. However, capacitors also are required which, in conjunction with the inductance in the line, slope the front of the wave and thus prevent pilin up of voltage across the turns. Present methods[1-7] of protection, on the whole, have proved quite satisfactory. However, in view of the statistical data that have been accumulated in extensive lightning investigations,[8-12] the recognition of the importance of providing good grounding for the line arresters, and the appreciation of the value of the inherently low discharge voltage characteristics of the deion arrester, it has been considered desirable to study this problem further.

The more important results of this study are summarized here with the viewpoint of providing a simple and straightforward basis for machine protection which affords the increased protection and saving in installation cost and material that it was found possible to achieve. Although the protection required at the machine and in the line are mutually interdependent, it is possible to resolve the suggestions for protection into the four following categories:

A. Protection at the machine terminal or bus.

B. Line protection for machines connected directly to overhead lines.

C. Line protection for machines connected to overhead lines through cables.

D. Protection of machines connected to lines through transformers.

Protection at the Machine Terminal or Bus

FIGURE 1 lists the valve-type machine-arrester and capacitor ratings recommended for each voltage class of machine together with their method of application. It is important that the arresters at the machine be valve type. They always should be applied with capacitors that are located either reasonably close to the arresters or between the arresters and machine. This combination prevents the occurrence of steep-front surges resulting from a sudden voltage drop when the arrester discharges.

Protection of grounded machines is obtained with a minimum amount of equipment. When more than one grounded machine is connected to a bus through short feeders, good lightning protection is provided with a single set of capacitors and arresters at the bus, provided that all exposed incoming lines are connected to the bus and there is no exposed line section between the bus and a machine. If more than 500 feet of line connects a machine to the bus, it is best to provide a set of capacitors and arresters at the machine. In some cases, machine-protective apparatus may be desirable for protection against switching surges. Then it should be placed on the machine side of the machine breakers.

Experience has shown that the present practice of applying the same amount of capacitance to ungrounded machines as for grounded machines up to 6,900 volts and of using double capacitance for 11,500 to 13,800 volts in general has provided satisfactory protection. This study, however, indicates that for certain conditions more positive protection of the neutral is desirable, and it can be obtained by the addition of a capacitor and arrester in the neutral with arresters and the same capacitance as used for grounded machines at the machine terminals. The neutral arrester prevents overshooting of voltage at the neutral from reflections. The capacitor prevents a steep neutral voltage rise and a sudden drop when the neutral arrester discharges. This method of protection can be justified economically for 11,500- to 13,800-volt machines where the neutral is brought out, where mounting space is available, and where protection is applied to each machine.

Where more than one ungrounded machine is connected to the bus, one set of arresters and two sets of capacitors may be applied to each phase at the bus, or preferably one set of capacitors and arresters on each phase at the bus and one set at the neutral of each machine.

In general, ungrounded machines require different machine-protective equipment from grounded machines only when they are connected directly or through cables to overhead lines.

Line Protection for Machines Connected Directly to Overhead Lines

Line arresters must be placed far enough out on the line so that sufficient equivalent inductance is present to produce, in conjunction with the machine capacitors, the required wave sloping. Five-hundred feet of line for 650-volt machines and 1,500 feet for all higher-voltage classes were commonly used in the past. A detailed study has been made of the machine-voltage conditions that can be produced with various circuit and line-arrester grounding conditions. The lightning-current investigations[8-12] indicate that line-arrester discharge currents of 20,000 amperes provide a conservative basis for such a study. One set of valve-type line arresters, 1,500 feet out on the line, will permit too steep machine-voltage fronts for ground resistances in excess of two to three ohms when overhead ground wires are not used. The new type-*A* deion arrester with its unlimited fault-current rating, obtained without the use of a series resistance, has been found more efficient for use as the line arrester because of its very low discharge voltage. However, even with one set of these, the grounding resistance should be limited to three to five ohms.

The two methods of line protection shown in Figure 2 are recommended for providing the most effective and economical schemes for general application. The scheme of Figure 2a is recommended where the section of line within the line arresters is exposed to lightning. The multiple arrester grounds provided by the overhead ground wire permit a minimum length of 500 feet for the ground wire when the listed pole-grounding resistances can be obtained. For this length of ground wire, sufficient direct-stroke protection is obtained with a line insulation level of 250 kv. If these ground resistances cannot be obtained with driven rods, a buried counterpoise can be used. The line construction usually will be more economical, even with the counterpoise, than a longer section of ground

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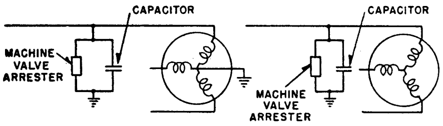
Table I

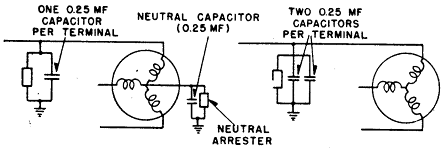
	Hydrogenerators and Other Slower-Speed Machines Machine—Kilovolt Class				Turbogenerators and Other Machines 1,800 Rpm and Above Machine—Kilovolt Class			
Transformer-Bank Connection	**2.4**	**4.16**	**4.8–6.9**	**11.5–13.8**	**2.4**	**4.16**	**4.8–6.9**	**11.5–13.8**
(*a*). Wye to delta on machine side								
Grounded systems—80 per cent arresters*	60	15	8	4	200	70	30	15
Ungrounded systems—100 per cent arresters	12	4	2	1	45	20	10	5
(*b*). Machine arresters and capacitors are recommended with wye–wye banks having both neutrals grounded								
(*c*). All other bank connections								
Grounded systems	20	6	4	2	70	30	15	7
Ungrounded systems	6	1.4	0.8	0.3	25	8	3	1.0

* Station arresters on line terminals of transformer.



(a). For all grounded machines and for ungrounded machines up to and including 6,900 volts. Arrester rating is determined by machine grounding conditions when mounted at machine but on system grounding when mounted at bus

Machine-Voltage Class	Surge Capacitors		Machine-Valve-Arrester Ratings (Rms-Kiovolts)	
	Micro-farads	Voltage Rating (Rms—Kilovolts)	Grounded	Ungrounded
For Grounded and Ungrounded Machines				
650	2.0	0.65	0.75	0.75
2,400	0.5	2.4	3.0	3.0
4,160	0.5	4.16	3.0	4.5
4,800	0.5	4.8	4.5	6.0
6,900	0.5	6.9	6.0	7.5
For Grounded Machines				
11,500	0.25	11.5	9.0	
13,800	0.25	13.8	12.0	


ONE 0.25 MF CAPACITOR PER TERMINAL
NEUTRAL CAPACITOR (0.25 MF)
TWO 0.25 MF CAPACITORS PER TERMINAL
NEUTRAL ARRESTER

WHERE NEUTRAL IS READILY AVAILABLE AND SPACE PERMITS

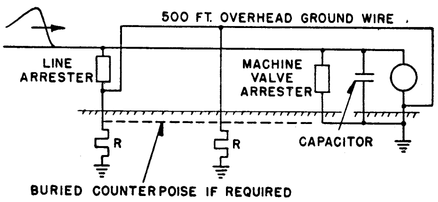
WHERE NEUTRAL IS NOT AVAILABLE OR NEUTRAL PROTECTION NOT ECONOMICAL

(b). For 11,500–13,800-volt machines with neutral floating, grounded through resistance or reactance exceeding 50 or 0.2 ohms, respectively, per 100 ohms of winding surge impedance. Minimum surge impedance can be taken as 100 ohms. If grounding impedance at 60 cycles is low enough, so that machine can be considered grounded from normal fault-voltage standpoint, the arresters listed under (a) may be used at the terminals, and the following may be used at the neutral:

Machine-Voltage Class	Terminal Equipment (Voltage Rating in Rms–Kilovolts)		Neutral Equipment (Voltage Rating in Rms–Kilovolts)	
	Capacitors	Arresters	Capacitors	Arresters
11,500	11.5	12	6.9	7.5
13,800	13.8	15	11.5	9.0

Figure 1. Apparatus requirements for lightning protection of rotating machines

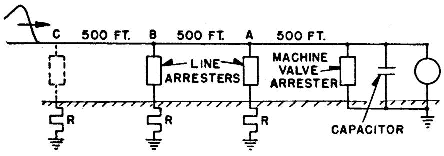
wire with higher pole-ground resistances, since an increase in line insulation level would be required also. For the case where an overhead ground wire is not used, Figure 2b, the benefit of multiple sets of line arresters arises from the fact that, for incoming surges, the farthest set of arresters discharges most of the surge current, permitting a much lower line-to-ground voltage at the inner sets.



(a). Cases where overhead ground wire is required for adequate shielding

Maximum Permissible Pole-Grounding Resistance, *R*, in Ohms		
Spacing of pole grounds (feet)	250	125
Type of line arrester		
Deion	5–10	10–20
Valve	2– 5	4–10

If these resistances cannot be obtained conveniently with driven ground rods, buried counterpoise connecting line arresters to machine ground may be used.



(b). Cases where overhead ground wire is not used (strokes to line within 1,000 feet may endanger machine)

Type of Line Arrester	Maximum Permissible Line-Arrester Grounding Resistance, *R* in Ohms	
	Two Sets of Arresters at *A* and *B*	Three Sets of Arresters at *A*, *B*, and *C*
Deion	10–20	20–40
Valve	5–10	10–20

Figure 2. Recommended line-protection methods for machines connected directly to overhead lines

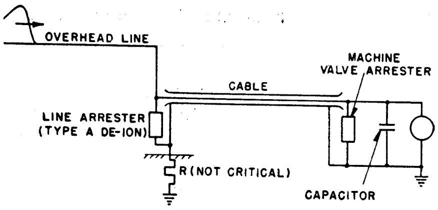
Machine-valve arresters and capacitors should be applied as described in Figure 1

Line Protection for Machines Connected to Overhead Lines Through Cables

Figure 3 lists the line protection recommended with cables connected between the line and machine. When line arresters are connected directly to the cable sheath through short leads, the voltage which can be transferred through the cable is only the arrester discharge voltage plus the drop across the short grounding lead. The much lower discharge voltage of deion arresters permits considerable simplification in the line protection. These schemes should be used only when deion arresters are applied at the cable pothead.

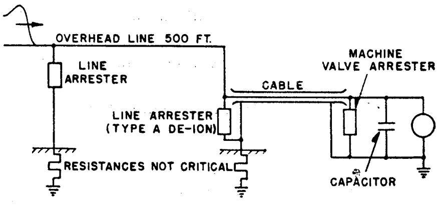
Protection of Machines Connected to Overhead Lines Through Transformers

The following steps provide a method of determining the lightning protection required for machines connected to exposed overhead lines through trans-



(a). For cables sufficiently long that section of overhead line is not required for wave sloping

Cable surge impedance in ohms	5	10	25	50
Minimum cable length in feet	2,000	1,000	500	300



(b). For cables longer than 200 feet, but not long enough to be classified under (a). Ground wire preferred but not essential

(c). For shorter cables the protection methods of Figure 2 are recommended with the addition of a set of deion arresters at the cable pothead

Figure 3. Recommended line-protection methods for machines connected to overhead lines through cables

Machine-valve arresters and capacitors should be applied as described in Figure 1. Data on cable surge impedance are given in Table III. Deion arresters at cable pothead should be interconnected to cable sheath formers. Since the transformer-leakage inductance is always sufficient for wave-sloping purposes, it is not necessary to provide arresters out on the line.

(*a*). Station-type arresters should be provided on the line side of the transformer bank.

(*b*). Both capacitors and machine-valve arresters should be used when the need for either is indicated.

(*c*). When machine protection is required, only one set of standard capacitors and machine-valve arresters is required at the machine terminals, regardless of whether the machine is grounded or ungrounded.

(*d*). Machine-surge-protective apparatus should be applied to protect against surges transferred electrostatically through transformers unless 50 to 100 feet of cable, providing an effective capacitance of 0.005 microfarad or more per phase, is connected to the machine terminals. The data on cable capacitance given in Figure 10 can be used.

(*e*). Machine-protection apparatus also should be used to protect against surges transferred electromagnetically unless both of the following conditions are satisfied:

1. C_1 is equal to or greater than $15/L$

where

C_1 = positive-sequence line-to-neutral capacitance of cable in microfarads

L = leakage inductance of transformer bank in microhenrys on line-to-neutral base referred to machine side

$$L=\frac{XE^2 10^7}{377(3\phi\ \text{kva})}$$

X = per cent leakage reactance of transformers

E = secondary line-to-line voltage in kilovolts

This condition assures adequate wave sloping.

2. C_1 is less than $(AL)10^{-6}$

where A has the values indicated in Table I. This condition limits the magnitude of the induced surge.

(*f*). This means of determining the use of protective apparatus is conservative. A more detailed method of calculation is given in the paper. The authors are of the opinion that in any doubtful cases protection should be applied, since the expense is small compared with the investment in machines. If machine-protection apparatus is not required for lightning surges, it still may be desirable for protection against switching surges. However, it is usually preferable to limit such surges by proper grounding methods.

Surge-Protection Levels

Consideration will be given first to the character of the voltages which it is safe to permit at machine terminals. Little direct data are available on the surge strength of the machine insulation and its variation with service. In Table II the standard AIEE crest 60-cycle voltage tests for machine line-to-ground insulation are compared with the protective characteristics of the machine-valve arresters recommended for each voltage class. That these provide safe protection has been demonstrated by ten years of field experience with many installations.

TURN-TO-TURN INSULATION

The turn-to-turn insulation of most modern large machines is designed and tested, so that each coil will stand full line-to-line rated voltage. This means that, if it is a two-turn coil, the insulation between turns will stand this full voltage. If it is a three-turn coil, it will stand one half of this voltage, and so on. However, many smaller motors and older machines were designed for only one-half this insulation strength. Most turbine generators have from one- to three-turn coils, while water-wheel generators usually have from two- to six-turn coils. Some smaller machines have as high as 40 turns per coil with 20-turn coils not uncommon. The standard practice of sloping the permissible surge voltage to a front of ten microseconds is adequate for coils with the higher number of turns. Fronts of three or four microseconds probably would not cause severe duty on one- or two-turn coils of modern large machines. However, the extent to which successive voltage impulses age machine

Table II. Protection Levels of Special Autovalve Machine Arresters

		Grounded Neutral Machine		Ungrounded Machine	
Machine Voltage Class	Standard AIEE 60-Cycle Test (Kilovolts—Crest)	Terminal Machine Arrester Rating (Kilovolts)	Gap Breakdown (Kilovolts)*	Terminal Machine Arrester Rating (Kilovolts)	Gap Breakdown (Kilovolts)*
650	3.3	0.75	2.5	0.75	2.5
2,400	8.2	3	9	3	9
4,160	13.2	3	9	4.5	13
4,800	15	4.5	13	6	17
6,900	20.9	6	17	7.5	21
11,500	33.9	9	26	12	34
13,800	40.5	12	34	15	42

* Breakdown for wave with ten-microsecond front. These values are not exceeded by the arrester discharge voltages (*RI* drop) for currents of the order of 2,000 amperes.

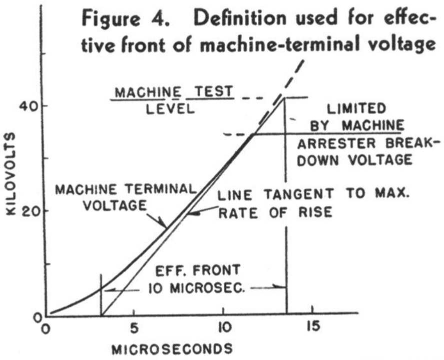


Figure 4. Definition used for effective front of machine-terminal voltage

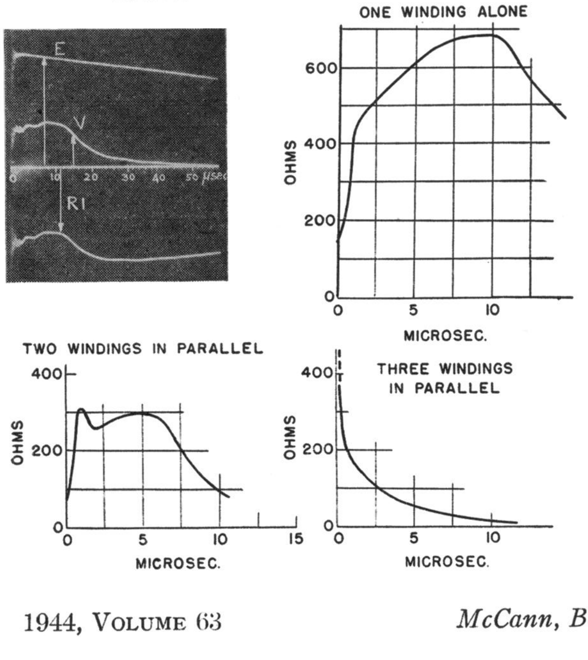


Figure 5 (left). Surge - impedance characteristics of 100-kva 2,400-volt synchronous machine used for grounding study

Figure 6 (right). Neutral voltage produced by various grounding resistance conditions

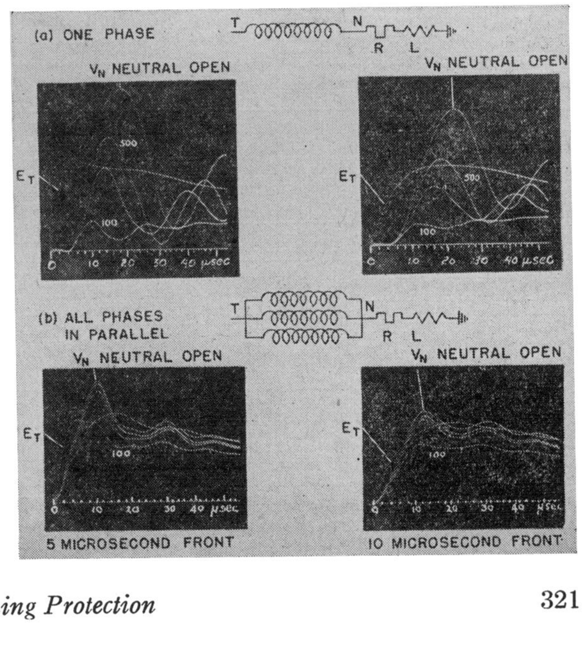
Impedance of the grounding resistances were as follows:

R = infinity

R = 500 ohms—L = 0.01

R = 250—L = 0.005

R = 100—L = 0.001



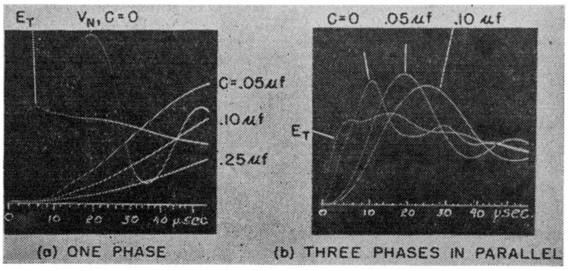


Figure 7 (left). Effect of neutral capacitance in sloping neutral voltage

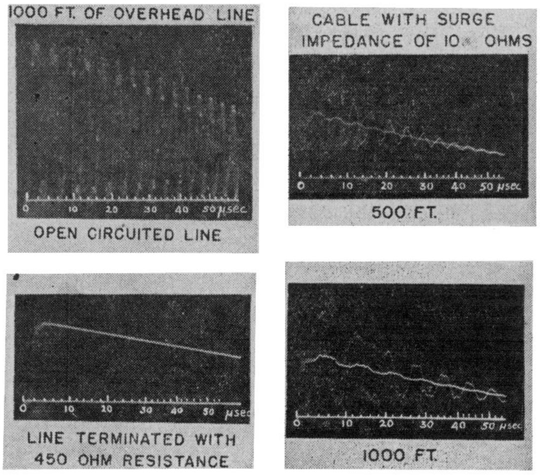


Figure 8 (right). Electrical characteristics of equivalent circuits used to represent overhead-line and cable sections

insulation in service is not clearly known. The conservative ten-microsecond front for all machines is still considered justified, not only for this reason but also to provide a uniform surge-protection basis. To obtain such a uniform basis for comparing various methods of wave sloping, the definition of the machine-terminal-voltage front given in Figure 4 is used throughout this paper. This limits the maximum voltage rise to a magnitude such that a uniform rise at this rate would not allow the test machine strength to be reached in less than ten microseconds.

Neutral Protection for Ungrounded or Impedance-Grounded Machines

The majority of machines are wye-connected. If the neutral is ungrounded or grounded through too high an impedance, reflections at the neutral for surges of the same polarity applied to two or more phases simultaneously may cause the neutral voltage to tend to double both in magnitude and rate of rise. The voltage will be highest for surges on all three phases, because the effective impedance of the three in parallel is less than for any other condition, and there is no additional phase left to act as a shunt impedance. If wave distortion and attenuation are neglected, and if the windings are considered as distortionless lines, the rate of voltage rise at the neutral of an ungrounded machine will be doubled for any incoming surge. Its magnitude will be doubled for any front less than two times the winding length, the overshoot decreasing for longer fronts. Winding lengths for a single-phase machine range from 5 to about 50 microseconds. Recommendations specifying the use of twice the machine-terminal capacitance for ungrounded machines have been based on limited tests which indicated that attenuation in the windings would prevent excessive neutral voltages if the front were increased to 15 or 20 microseconds. Whether or not this is true for all machines, the use of a neutral arrester to limit the crest voltage and a neutral capacitor to limit the rate of voltage rise provides a more positive method of protection. The neutral arrester has been used with success. It generally has been an obsolete type of gapless arrester which would not permit a sudden voltage drop following gap spark-over. An abrupt drop produces a steep-front surge propagating back through the windings which might overstress the turn-to-turn insulation. The use of conventional arresters in the neutral, therefore, has been criticized.[5] However, a capacitor in parallel eliminates this severe drop at the neutral and the terminal arresters, as pointed out by Calvert and Roman.[6]

Surge tests were made on a 2,300-volt 100-kva synchronous machine having five-turn coils and no parallel sections. Its surge-impedance characteristics are shown in Figure 5. These curves were obtained by applying a square voltage wave to each winding combination connected in series with a resistor and by measuring the current and voltages at the machine terminals. As shown, the windings at no time have a constant surge impedance; however, after about one microsecond the variation is not very great, for the cases of one winding alone or two in parallel, until reflections from the neutral reach the terminals. The

Table III. Effective Surge Impedance in Ohms of Paper-Insulated Cables*

Conductor Size (American Wire Gauge or Circular Mils)	Belted Cables* Voltage Classes					Type-H Cables
	0–1 Kv	2–3 Kv	4–5 Kv	7–8 Kv	14–15 Kv	14–15 Kv
Three-Conductor Cables						
4	29	31	34	36	42	22
1	22	25	30	30	36	17
00	14	17	22	23	29	15
250,000	11	13	15	19	23	11
500,000	8	9	12	13	17	9
750,000	5	7	9	10	13	8
Single-Conductor Cables						
4	14	16	19	24	33	
1	11	12	14	20	24	
00	8	10	12	16	22	
250,000	6	8	9	13	17	
500,000	4	6	7	10	13	
750,000	5	6	6	8	11	
1,000,000	4	5	5	7	10	
1,500,000	4	4.5	4.5	6	8	

Specific inductive capacity k = 3.7. Velocity of propagation $v = 512$ feet per microsecond.

* Effective surge impedance for surge propagation on only one phase. This is the most severe condition. For single-conductor and type-*H* cables this is the positive-sequence surge impedance. For belted three-conductor cables, it is equal to 4/3 the positive-sequence surge impedance.

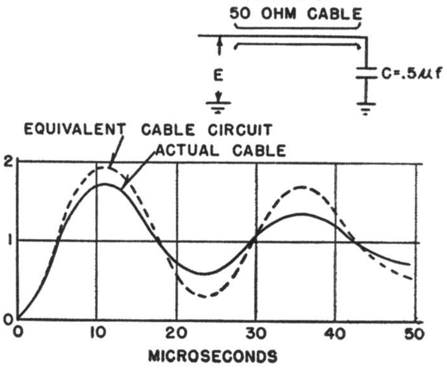


Figure 9. Comparison between solution obtained with actual cable and its equivalent circuit

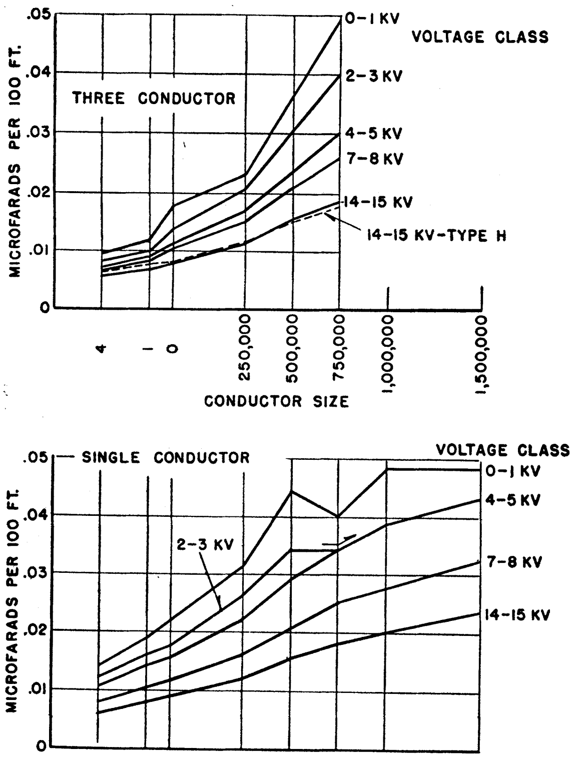


Figure 10 (left). Positive-sequence capacitance of paper-insulated cables

Three-conductor belted and type-*H* cables, and single-conductor concentric-strand cables

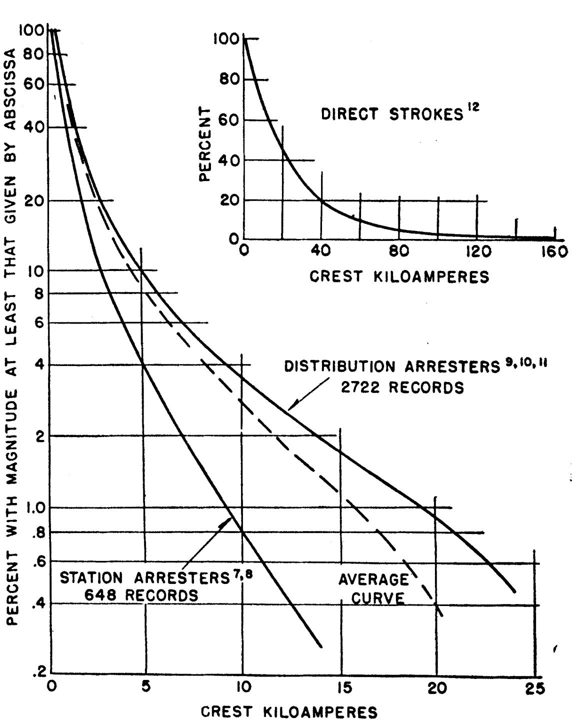


Figure 11 (right). Probability curves for crest magnitude of lightning discharge currents

electrical length for one winding is about five microseconds, and for two in parallel, it is about three microseconds. However, the three windings in parallel act more like a lumped inductance and show little distributed capacity effect. Mutual coupling between phase groups distributed around the armature induces voltages more nearly simultaneously in all coils of each phase reducing greatly the effective electrical length.

Effect of Grounding Resistors

The cast grid resistors most commonly used for neutral grounding have about one-millihenry inductance for each 50 ohms of resistance at a frequency of 50,000 cycles per second, which corresponds to the surge fronts being considered. Figure 6 shows the effect of grounding impedances of this type on the neutral voltage. The five-microsecond front used for the terminal voltage E_T in the left-hand set of oscillograms is equal to the electrical length of one winding alone and more than double the effective length of the three in parallel. The terminal voltages used for the right-hand set of oscillograms has an effective front between 10 and 15 microseconds, which is about three times the length of one winding and at least six times that of the three windings in parallel. These tests, therefore, are representative of a range of conditions. Figure 6 shows that overshooting of the neutral voltage is permitted by resistors of 250 ohms or more for the three windings in parallel, even for the slower front. This indicates that 15- to 20-microsecond fronts at the terminals produce severe neutral voltages in machines with longer windings, unless there is considerably more damping than appears in this machine. Overshooting occurs for grounding resistances as low as one-half the surge impedance of one-phase winding. The lower limit of machine surge impedance is about 100 ohms. Thus, unless sufficient data are available on the surge impedance, a machine should be considered as ungrounded for any conventional resistance above 50 ohms.

Grounding Reactors

Neutral voltage overshooting in this machine did not occur for inductances of less than about 2.5 millihenrys or a reactance at 60 cycles of 0.9 ohm. For the lower limit of machine surge impedance, a 60-cycle reactance of 0.2 ohm or less should not cause excessive neutral voltage. For more than 0.2-ohm reactance per 100 ohms, surge-impedance neutral protection should be provided.

Table IV. Maximum Safe Line-Arrester Ground Resistances Permitted by the Various Protection Schemes of Figure 19 Based on Protection Against 20,000-Ampere Arrester Discharge

Maximum Permissible Line-Arrester Ground Resistance in Ohms

		A One Set Line Arresters 1,500 Feet Out on Line (No Ground Wire)		B Two Sets Line Arresters (No Ground Wire) See Figure 19		C Three Sets of Line Arresters (No Ground Wire) See Figure 19		D One Set Arresters Connected to Ground Wire—See Figure 19		E Two Sets of Arresters Interconnected to Ground Wire—See Figure 19	
Machine-Voltage Class	Terminal Capacitance (Microfarads)	Valve Arresters	Deion Arresters	Valve Arresters	Deion Arresters	Valve Arresters	Deion Arresters	Valve Arresters	Deion Arresters	Valve Arresters	Deion Arresters
650	2.0	2*		5		10		5		15	
2,400	0.5	1	2.5	2.5	5	5	10	1	2.5	3.5	7
4,160	0.5	2.5	5	4	8	6	10	2	4	6	12
4,800	0.5	1	2.5	2.5	6	4	7	1	2.5	4	8
6,900	0.5	1	3	3	7	5	10	1.5	3	5	12
11,500	0.25	1	4	4	10	7	15	2.5	5	10	20
13,800	0.25	1	5	5	12	10	20	3	7	12	25

* 500 feet for 650-volt class.

Table V. Required Inductance of Choke Coils for Protection of Machines Connected to Overhead Lines Through Cables

Machine Voltage Class	Terminal Capacitance (Microfarads Per Phase)	Minimum Cable Length (Feet)	Choke-Coil Inductance in Microhenrys Per Phase			
			5-Ohm Cable	10-Ohm Cable	25-Ohm Cable	50-Ohm Cable
650	2.0	0*	25	25	25	25
		250	20	20	20	0
		500	15	10	0	
		1,000	10	0		
		2,000	0			
4,160	0.5	0	25	25	25	25
		250	20	10	0	0
		500	10	0		
		1,000	0			
		2,000				
2,400 4,800 6,900	0.5 for all but 6,900 ungrounded where $C=1.0$	0	50	50	50	50
		250	40	30	25	0
		500	25	20	15	
		1,000	20	10	0	
		2,000	0	0		
11,500 13,800	0.25 except for 11.5 kilovolts ungrounded where $C=0.5$	0		50	50	50
		250		35	25	15
		500		25	15	0
		1,000		10	0	
		2,000		0		
Alternative 6,900 ungrounded 11,500 ungrounded	0.50 0.25	0	75	75	75	75
		250	50	50	50	25
		500	35	30	35	10
		1,000	25	20	20	0
		2,000	15	0	0	

* Cables less than 200 feet in length.

DELTA MACHINES

Similar tests made with the machine connected in delta showed somewhat higher voltages and rates of voltage rise at the midpoint of each phase than indicated in Figure 6 for the neutral open-circuited. For delta- or wye-connected machines, the neutral of which is inaccessible, the only practical method of protection is the use of sufficient capacity at the machine terminals to prevent overshooting. These tests indicate that, for machines of longer winding lengths, more capacity should be used than recommended in the past. However, in view of satisfactory experience, it is believed that the capacitance that has been recommended is generally adequate. If neutral protection can be applied, it is the most effective scheme where neutral protection is required. This material applies only to machines connected directly to overhead lines. Machines connected through transformers will be considered later.

CAPACITANCE REQUIRED FOR SLOPING NEUTRAL VOLTAGE

Figure 7 shows tests made to determine the amount of neutral capacitance required for adequate sloping. A given amount of capacitance is less effective for lower-winding surge impedances. However, 0.05 microfarad is more than sufficient for this machine. One-quarter microfarad (the lowest value now commonly used for surge-protective capacitors) should be ample for machines of lowest surge impedance. Since these are machines with one- or two-turn coils, the steeper fronts would be permissible, and this value is not critical. Calvert and Roman[6] show that about 0.175 microfarad is required to prevent a severe drop in voltage when the arrester discharges. Similar tests made in this investigation (see Figure 29) show that 0.25-microfarad capacitors are adequate. The capacity used at the machine terminals is recommended for the neutral.

Methods of Analysis

When calculating the machine-terminal voltages produced by traveling waves, analytical solutions are practical for the simpler cases in which the voltage at the line-arrester location can be expressed by a square wave, and only a continuous single section of line or cable is connected between it and the capacitor. However, for more complex cases, it is simpler and more accurate to set up equivalent circuits, produce the desired voltage or discharge current at the line arrester with a surge generator, and measure the terminal voltages with a cathode-ray oscillograph. It was found that overhead-line sections can be represented to sufficient accuracy for this study by using one equivalent Π circuit for each 125 feet. These consisted of series inductance and shunt capacitance. For cables one Π circuit was used for each 62.5 feet. The electrical characteristics of some of these circuits are shown in Figure 8. The coils for the overhead-line sections had resistance about equal to the surge resistance of an actual conductor. Low-loss condensers were used, and most of the damping was

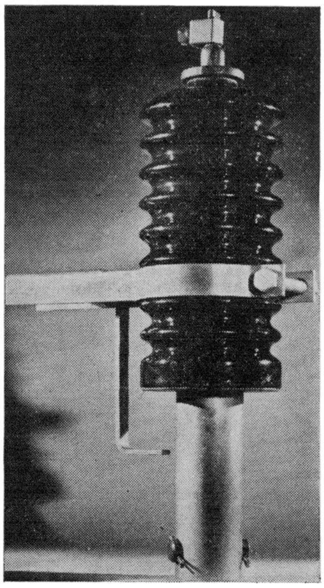
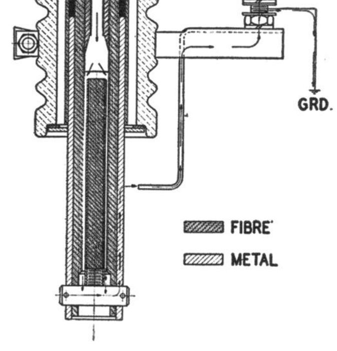


Figure 12. Nine-kilovolt type-*A* de-ion arrester



TYPE A 'DE-ION' PROTECTOR TUBE

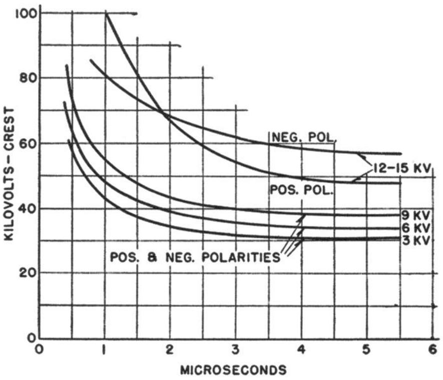


Figure 13. Spark-over characteristics of the new type-*A* deion arresters

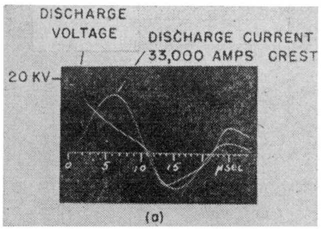
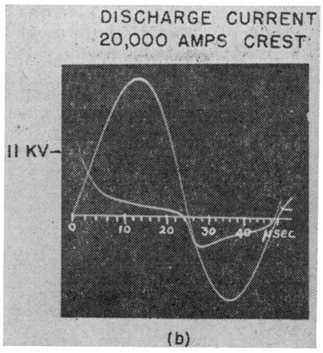


Figure 14. Discharge-voltage characteristics of six-kilovolt type-*A* deion arrester



in the coils which had Q factors ranging from 200 to 300 at one megacycle. Damping in the circuits representing cable sections, in most cases, was somewhat less than that of an actual cable. Figure 9 shows a comparison between the solutions obtained with an actual 50-ohm cable and its equivalent circuit. When cases with 0.25 microfarad or more connected to the machine terminals are considered, the machine does not have to be represented. Its impedance is always sufficiently high compared with that of the capacitors at the frequencies of the circuits being considered. Single-phase circuits were used for most cases, the circuit constants being chosen so as to represent the most severe condition. This is usually for a surge on only one phase, because the product of the effective machine-terminal capacitance and line or cable surge impedance is always as great or greater for surges on more than one phase than for a surge on a single phase. A surge impedance of 450 ohms was used for overhead lines.

SURGE IMPEDANCE AND CAPACITANCE OF CABLES

For surges propagating through a circuit containing either single-conductor or type-*H* three-conductor cables having each conductor individually shielded, the positive-sequence surge impedance should be used. For other three-conductor cables, the most severe condition is given by a surge impressed on only one conductor. However, since it is electrically coupled with the other two conductors, the effective single-circuit surge impedance for this case is a function of both the positive- and zero-sequence surge impedance. For all cables of the voltage class used in machine circuits, the positive-sequence surge impedance is very nearly equal to one half of the zero-sequence surge impedance, and the effective single-circuit surge impedance is quite close to four thirds of the positive-sequence values. Table III lists the effective surge impedances of the paper-insulated cables commonly used for machine circuits. Figure 10 gives the positive-sequence capacitance of these cables.

The surge-voltage to ground at the line arresters is a governing factor in determining the machine-terminal voltages. After spark-over this is the impedance drop in the arresters and their grounds. It is also necessary to consider the voltage which can occur at the machine before the line arresters discharge or for surges propagating into the machine, the magnitudes of which are below the arrester spark-over voltage. Data, therefore, are required on the characteristics of the line arresters and the lightning currents, on which they may be called to discharge.

CHARACTERISTICS OF LIGHTNING DISCHARGE CURRENTS

Crest Currents. Lightning current measurements have been made in several extensive investigations.[8–12] Probability curves for both distribution and station arresters are given in Figure 11, together with similar data on direct strokes. Distribution arresters are subject to a greater percentage of higher-magnitude surges. The line arresters for machine protection probably operate under conditions more closely approaching those of the station arresters. Balanced against their greater chance of receiving high-current discharges by being cut on the line is the fact that they are used on shorter lines of lower insulation than represented by Figure 11. It is thought that the average curve of Figure 11 provides a conservative basis for this application. The highest current recorded at a station arrester is about 15,000 amperes. The highest at a distribution arrester is somewhat above 30,000 amperes. These curves are based on individual arrester discharges. Data available from the three-phase station arrester studies enable a conversion of this to the probability of a disturbance (which may involve from one to all three arresters) producing a given magnitude discharge. Analysis of these data has shown that the average curve indicates a probability of about one 20,000-ampere discharge every 140 years at an arrester bank.

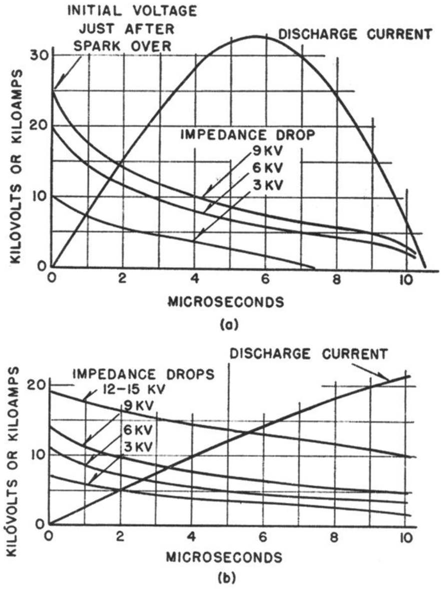


Figure 15. Discharge-voltage characteristics of type-*A* deion arresters

Wave Shape. The principal range of times to half value of arrester currents is 20 to 100 microseconds[9] with an average of 45. The maximum average rate of rise that has been recorded in the Westinghouse investigation[9] from 82 station-arrester wave-front measurements is 7,500 amperes per microsecond. After all of the factors are considered, it is believed that recommendations for the protection of important installations should be based on line-arrester discharges of 20,000 amperes with a two-microsecond effective front or an average rate of rise of 10,000 amperes per microsecond. Since consideration need be given to the machine-voltage wave shape for the first 10 or 15 microseconds only, the assump-

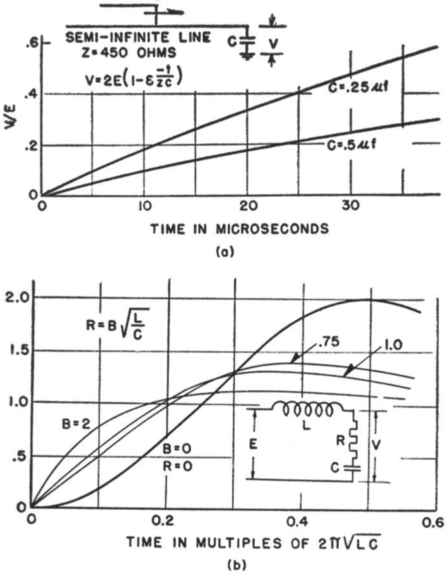


Figure 16. Curves giving general solutions for square voltage waves applied to machine surge-protection circuits

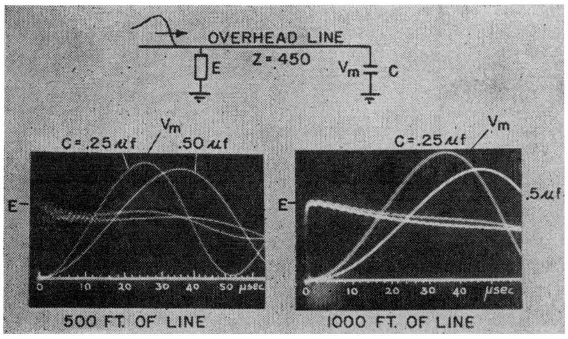
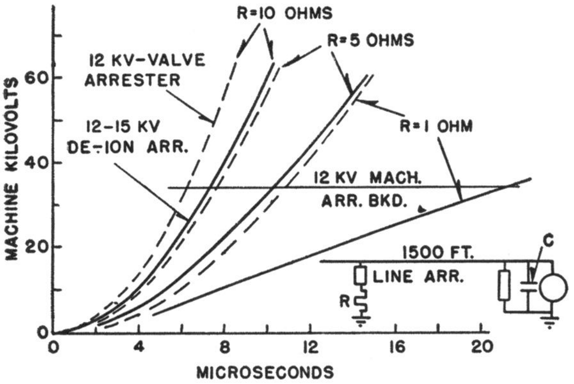
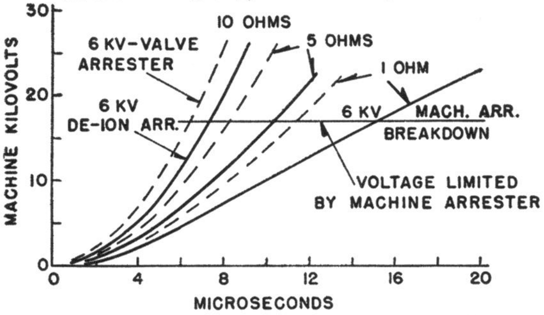


Figure 17 (left). Typical solutions of machine terminal voltage obtained with equivalent circuits



(a) 13.8 KV MACHINE, 1500 FT. LINE, C=0.25μf



(b) 6.9 KV MACHINE, 1500 FT. LINE, C=0.5μf

Figure 18 (left). Machine terminal voltages as a function of line-arrester ground resistance when one set of line arresters is used with no overhead ground wire

Based on 20,000-ampere line-arrester discharge current

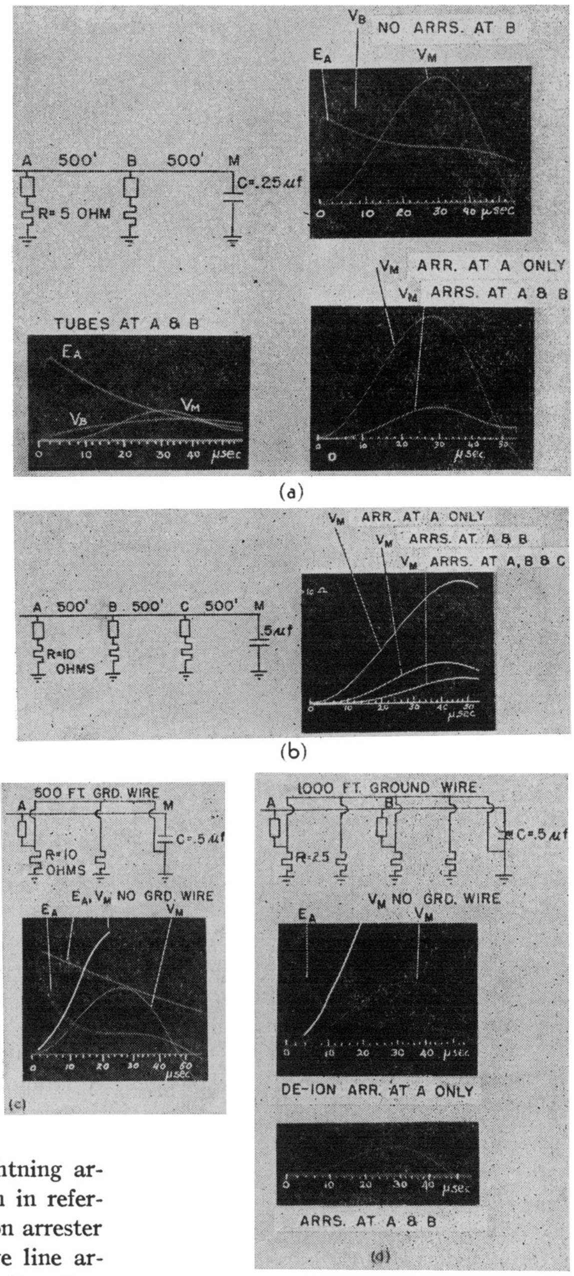


Figure 19 (right). Oscillograms showing reduction of machine voltages when multiple sets of line arresters or interconnection to overhead ground wire is provided

(a). Two sets of deion arresters with no overhead ground wire

(b). Three sets of deion arresters—no ground wire

tion of an infinite tail for the discharge current gives good accuracy and is conservative. For purposes of analysis and comparison of various protective methods, this discharge current will be used as a basis. Consideration will be given then to the variation in protective methods justified for cases of less importance or where lightning conditions might not be so severe. It will be shown that, for the methods of protection recommended in this paper for machines connected directly or through cables to overhead lines, higher discharge currents would only have the effect of shortening somewhat the front of the machine-terminal voltage. The crest magnitude, which is more important, would be limited to a safe value.

Characteristics of Protective Devices for Line Application

Distribution valve-type lightning arresters have been used mostly for the line arresters of machine-protection circuits. Average characteristics for these, as compiled by the AIEE lightning arrester subcommittee, are given in reference 14. The new type-*A* deion arrester (Figure 12) is a more effective line arrester for this particular application than are the valve arresters. Although its spark-over voltage (Figure 13) on steep-front surges is slightly higher than that of the valve arrester, the voltage across its terminals during discharge collapses quickly to relatively low values, as shown by the impedance-drop curves of Figures 14 and 15. Consequently, this deion arrester will transmit less surge energy to the machine capacitor, thereby improving the protection to the machine. Likewise, conditions at the line arrester may be more severe without impairing the degree of protection. For example, the impedance drop in the six-kilovolt deion arrester (Figure 15a) for a rate of current rise of 9,000 amperes per microsecond is 20 kv just after spark-over, but drops to about six kilovolts at the peak of the discharge. It will be shown that, as far as charging the machine capacitor is concerned, the effective impedance drop of this arrester is an equivalent square-topped voltage wave of not more than ten kilovolts, as compared with an *IR* (current-resistance) drop of about 30–34 kv for a valve arrester at the same discharge current. For a discharge current of 1,500 amperes, the equivalent square-topped voltage for the tube will range from one to four kilovolts for the 3- to 15-kv arresters. This deion arrester has an unlimited current-interrupting capacity without a series resistance which would produce a much higher discharge voltage.

Voltage Conditions Before Line Flashover or Arrester Breakdown

Before flashover occurs or a line arrester discharges, the machine-terminal voltage is determined by a wave propa-

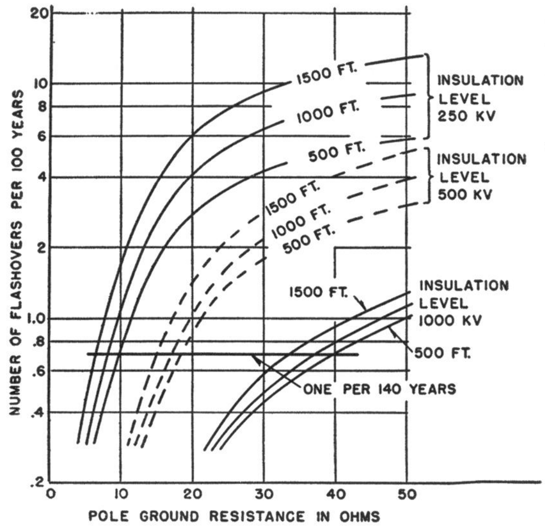


Figure 20 (left). Efficiency of overhead ground wire of various lengths as function of line insulation and pole-ground resistance

Based on density of one stroke per mile of line per year, direct-stroke-current probability curve of Figure 11, and current - wave - shape data of reference 17

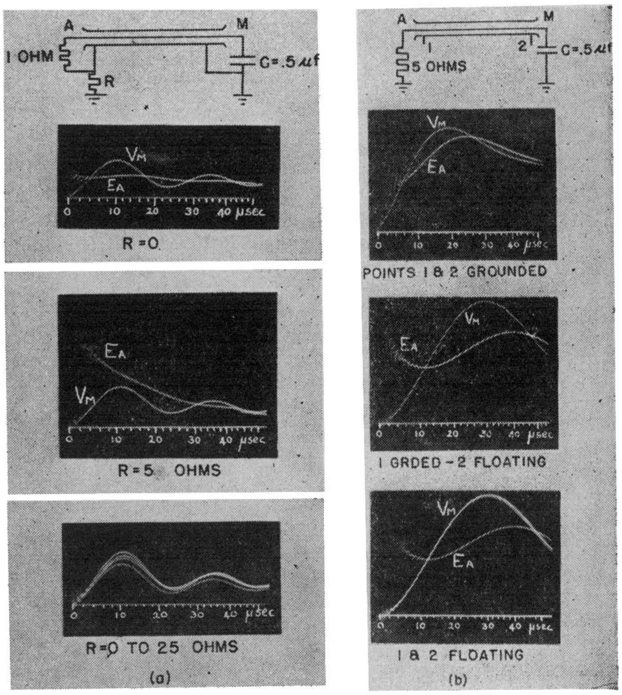


Figure 21 (right). Effect of sheath grounding on surges transferred through cables

gating in from a great distance. Figure 16a gives such a solution for a square wave. It can be seen readily that, unless a reflection point is established by flashover close to the machine terminals, no severe voltage condition will be permitted by the deion arresters. For instance, the maximum square-wave voltage that the 12–15-kv arrester will permit is 57 kv for negative polarity. Figure 16a shows that, for $C=0.25$ microfarad, the machine voltage produced in ten microseconds by this wave could be only about ten kilovolts, which is sufficient sloping even for a 2,400-volt machine.

Voltage Conditions Produced by Flashover and Arrester Discharge

Strokes producing line flashover establish a point of reflection. During the period before a line arrester discharges, the machine-terminal voltage is determined by the voltage maintained at the point of flashover and the circuit constants between this point and the capacitor. After a line arrester discharges, the machine-terminal voltage can be determined from the line-arrester location and voltage. It was found that, in practically all cases where a stroke produced flashover beyond the line arresters, the machine-terminal voltage before the line arresters discharge is insignificant. Strokes occurring to an unshielded line within the line arresters are likely to cause flashover so close to the machine that insufficient line inductance is available for wave sloping. Also, severe current duty is likely to be imposed on the machine arresters resulting in too high discharge voltages. Adequate protection from this can be secured only by providing adequate shielding, and the probability of such direct strokes, therefore, must be considered. The machine voltage produced by the voltage main-

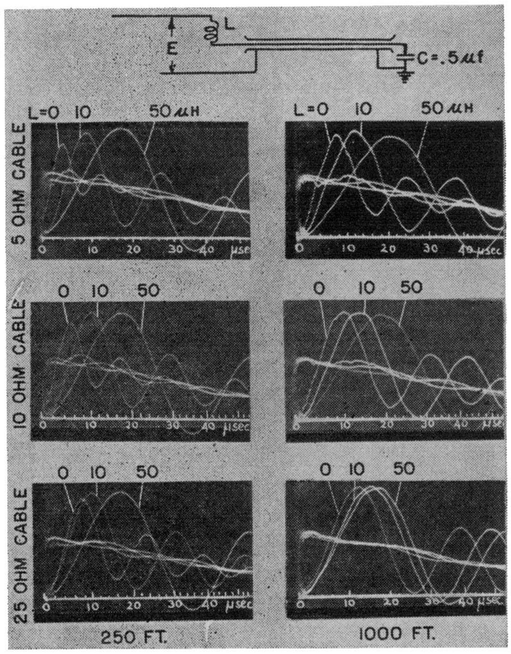


Figure 22 (left). Typical solutions for machine voltage obtained with equivalent circuits for cables of various lengths and surge impedances, and for a range of choke-coil inductances

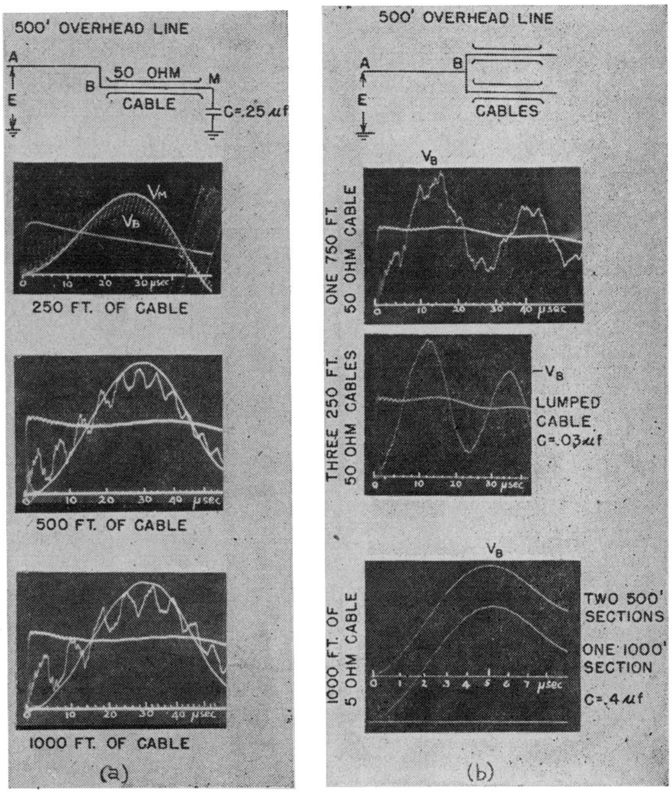


Figure 23 (right). Typical solutions for a range of cable-circuit conditions

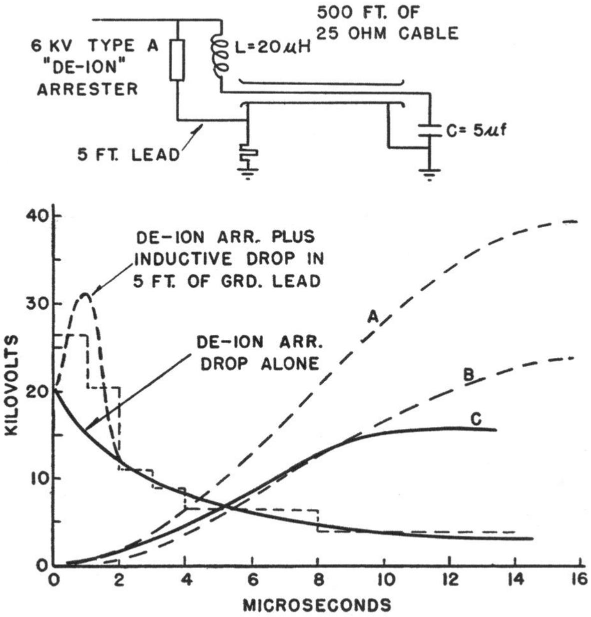


Figure 24 (left). Method for calculating machine voltage produced by actual line-arrester voltage from solutions such as those of Figures 22 and 23 for square voltage waves

A. Machine voltage for a 20,000-volt square wave at arrester

B. Machine voltage for a 12,000-volt square wave

C. Actual machine voltage permitted by the deion arrester

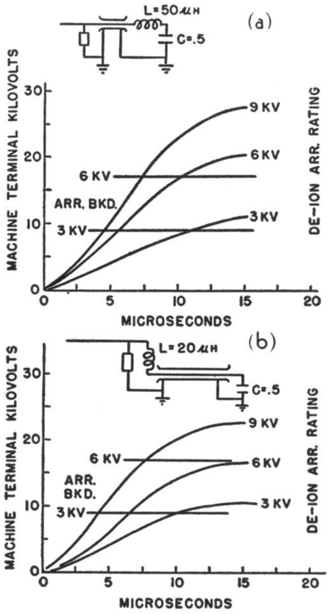


Figure 25 (right). Typical solutions for voltages permitted by deion arresters at cable potheads only

Arrester discharge of 20,000 amperes with two-microsecond front

(a). Very short cables

(b). Cable — 500 feet, 25 ohms

tained at the line arresters[5] after they spark-over will be the principal consideration in this analysis. The other conditions will be considered where they are important.

For circuits representing one set of line arresters and only a single section of overhead line between the arresters and machine capacitors, the line can be represented by a lumped inductance. The effect of the line capacitance is negligible compared with a machine-terminal capacitance of 0.25 microfarad or more. The general solution for a square voltage maintained at the end of an inductance connected to a capacitance is given in Figure 16b by the curve for R equal zero. Typical solutions obtained with the equivalent circuits are shown in Figure 17. These solutions cannot be distinguished from those calculated by the curve of Figure 16b. For most of the more complex cases considered, a solution was obtained with the equivalent circuits and a square voltage across the line arresters. The solution for the actual voltage that would be produced across the line arrester, its lead inductance, and its ground resistance then was determined by the superposition method applying a series of square waves to approximate the actual line-arrester voltage. An example of this is shown in Figure 24.

Machines Connected Directly to Overhead Lines

Two general methods are available for obtaining the necessary inductance for wave sloping. One is to provide a set of choke coils between the line and machine capacitors with line arresters on the line side of the coils. The other is the use of the line inductance. Several factors should be considered in comparing these two methods. Choke coils have the advantage that a ground wire is not required to insure against direct strokes to the line section. Also, the line arresters can be placed at the machine bus and their grounds interconnected with the machine grounds to eliminate the arrester-ground resistance drop. On the other hand, the coils must be designed for adequate short-circuit and continuous current conditions. Their necessary size and construction features frequently have made them difficult to apply.

Choke Coil—Capacitor Method

A comparison was made of the necessary inductances and capacitances required when either valve or deion arresters are used as the line arrester. It was found that, if two of the standard capacitor units listed in Figure 1 are used at each machine terminal, the necessary choke-coil inductance is 175 microhenrys per phase when valve arresters are used as the line arresters. When type-A deion arresters are used, the inductance can be reduced to about 90 microhenrys.

Method Using Line Section for Wave Sloping

One Set of Arresters 1,500 Feet Out on Line—No Ground Wire. Calculations of the machine voltages produced by the 20,000-ampere-arrester discharge with two-microsecond front have been made for each voltage class and a range of grounding resistances. Several of these

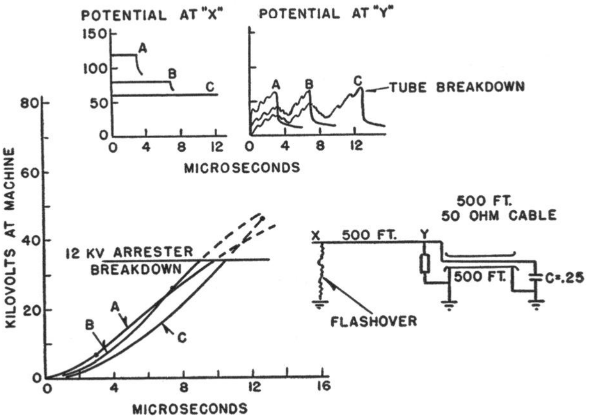


Figure 26. Typical calculation of voltages produced by line flashover 500 feet out on overhead line

Potential at Y determined from Figure 23a

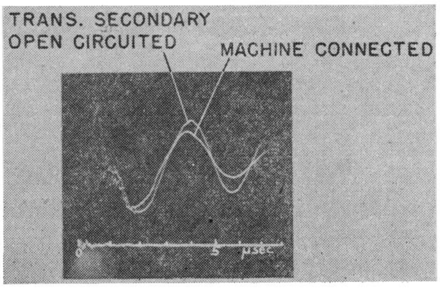


Figure 27. Comparison of voltage transferred through transformer bank when secondary winding is open-circuited and connected to rotating machine

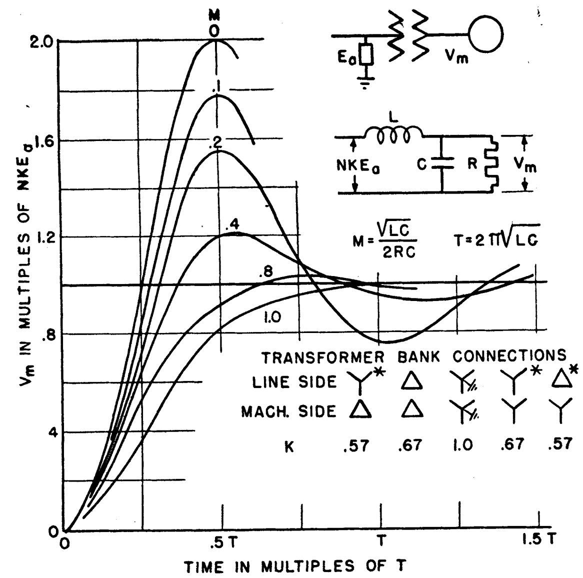


Figure 28. Equivalent circuit and solutions for determining the machine terminal voltages transferred electromagnetically through transformer banks

E_a = station-arrester line-to-ground discharge voltage
N = ratio of machine to line phase-to-phase rated voltage
L = leakage inductance of transformer bank in microhenrys on line-to-neutral base referred to machine side
C_1 = positive-sequence line-to-neutral capacitance in microfarads of cables or machine-protective capacitors connected to machine side of transformer bank
R = effective resistance in ohms given by paralleling surge impedances of all machines connected to transformer bank
V_m = machine terminal surge voltage *Applies to grounded or ungrounded wye

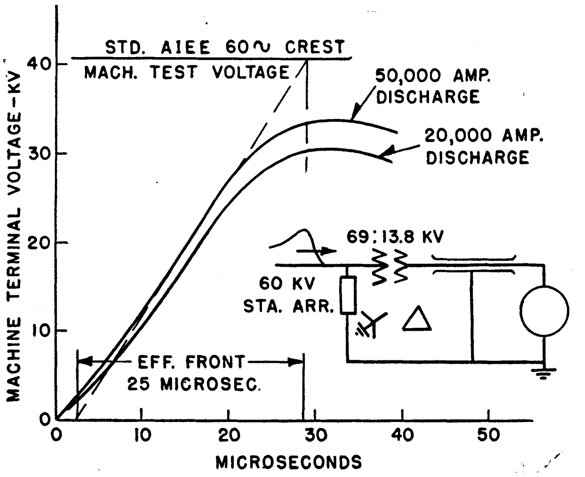


Figure 29. Machine terminal lightning surge voltage as calculated from Figure 28

10,000-kva 13.8-kv machine (surge impedance R = 500 ohms). One hundred feet of 750,000-circular-mil type-H cable between transformers and machine (from Figure 10, C_1 = 0.0175 microfarad). Transformer leakage reactance = 8.5 per cent (L = 4,200 microhenrys). Station arrester E_a = 234 kv at 20,000 amperes and 260 kv at 50,000 amperes. From Figure 28, $0.5T$ = 26 microseconds, M = 0.47, $NKE_a = 0.2 \times 0.57 E_a = 0.114 E_a$

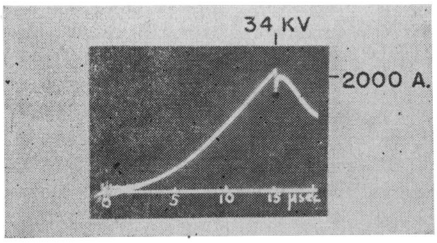
are shown in Figure 18. For this case, 30-foot line-arrester ground leads were assumed. As shown by Figure 18, the machine-terminal voltage in most cases is too steep when valve arresters are used with a ground resistance above one ohm. For deion arresters the permissible resistance ranges from 2.5 to 5 ohms. Even this resistance is frequently difficult to obtain.

Multiple Sets of Line Arresters—No Ground Wire. The high rates of machine-voltage rise permitted by one set of line arresters with high ground resistance can be reduced very effectively by the use of more than one set spaced at intervals along the line. This is illustrated in Figures 19a and 19b for cases where deion arresters are used. The benefit results from the fact that initially practically all of the surge current will be discharged by the arrester farthest out on the line. The percentage of current which initially flows past this point to the next arrester set depends on the ratio of the arrester ground resistance to the line surge impedance. The rate at which it increases depends on this and the distance between the arresters. It was found that the optimum distance between arrester sets for this application is about 500 feet. For the test shown in this figure, the discharge current flowing into the point A had a 70-microsecond tail. As shown by the left-hand oscillogram of Figure 19a, when two arrester sets are used, the voltage at the second arrester builds up slowly and does not exceed about one fourth of the maximum voltage across the first arrester. The machine-terminal voltage is also reduced to about one fourth of the magnitude permitted by one set of arresters at A only. Figure 19b shows the added benefit of a third set of arresters 1,500 feet out on the line.

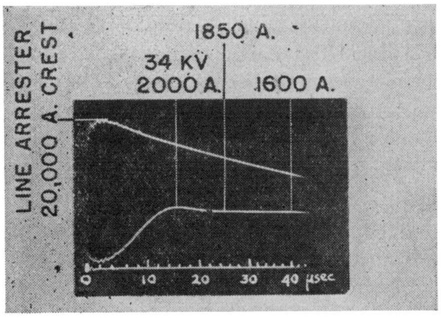
In column B of Table IV are listed the grounding resistances permitted by two sets of arresters. When valve arresters are used, the range is 2.5 to 5 ohms. For deion arresters, it is 5 to 12 ohms. Column C gives similar data for three sets where the corresponding ranges are 5 to 10 ohms and 10 to 20 ohms, respectively. In determining these values, consideration was given also to the current surges of lower magnitude which would not discharge the inner sets of arresters. The most severe voltages that can be produced under these conditions are about equal to that set up by the 20,000-ampere surge.

Benefits of Interconnection With Overhead Ground Wire. Aside from shielding, the interconnection of grounds provided by a ground wire is of considerable benefit. This is illustrated in Figures 19c and 19d for ground-wire lengths of 500 and 1,000 feet. For these two cases, pole-ground leads were spaced at 250-foot intervals providing about the minimum number of grounds that would be used normally. The shorter the ground wire the greater the benefit it provides in interconnecting the line arresters to the machine or bus ground. Balanced against this, however, is the steeper front resulting from shorter lengths of phase conductors. The minimum distance found practicable is about 500 feet. As shown by Figure 19c, the voltage and current at the line arrester has been reduced greatly after about 12 microseconds for the 500-foot case. Thus, the benefit of the ground wire is considerable. Columns D and E of Table IV show the ground resistances permitted for these two cases. The 500-foot ground wire permits resistances only about 25 per cent below those of column B, where two sets of line arresters and 1,000 feet of line are used. When the interval between pole grounds is cut in half, the permissible grounding resistances can be about doubled, thus allowing an upper limit of about 15 ohms for the 500-foot ground wire and 50 ohms for the 1,000-foot ground wire when deion arresters are used.

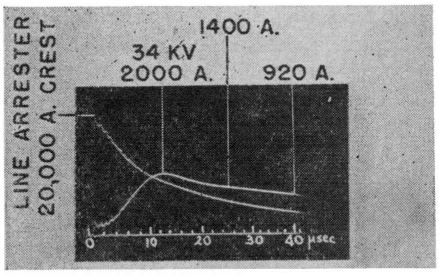
Probability of Direct Strokes Within Line Arresters. The exposure of this section of line to direct strokes will vary widely for different cases. It usually will be less than the average for the total line, since there frequently are shielding structures, such as buildings and other lines near by. However, the only direct data available on the frequency of direct strokes pertain to whole lines. The most complete data are those of Waldorf[15] for 66- to 220-kv circuits, which indicate a range of 50 to 250 strokes per 100 miles of line per year with a general average of 100 for isokeraunic levels between 25 and 40. Limited data obtained on 33-kv wood-pole lines indicate the same general average. For estimating purposes this is thought to be applicable to exposed lines of the voltage classes considered here. It is probably too high for the section of line adjacent to the machine station in most cases. When the value of 100 strokes per 100 miles of line per year is used, the probability of direct strokes occurring within the farthest set of line arresters is about once every ten years for each 500 feet. The shortest practical length of line when no overhead ground wire is used is the 1,000 feet for the case of column *B*, Table IV. The possibility of 20 strokes every 100 years or a stroke every five years within this length is thus indicated. This is much greater than the estimated probability of once every 140 years for a 20,000-ampere discharge through the line arrester. Even if the estimate of direct strokes were high by a factor of 10 or 20, the overhead ground wire should be used to equalize the two probabilities.



(*a*). Discharge voltage of actual 12-kv machine arrester. Parallel capacitance = 0.25 microfarad



(*b*). Discharge voltage and current for 1,500-foot line and 10 ohms ground resistance at line arresters. $C = 0.25$ microfarad



(*c*). Discharge voltage and current for 500-foot ground wire interconnected to line arresters. 10 ohms ground resistance. $C = 0.25$ microfarad

Figure 30. Typical machine-arrester discharge current and voltage obtained with model circuits (*b*) and (*c*) as compared with characteristics of actual arrester (*a*)

Recommended Overhead Ground-Wire Construction. The four principal construction factors determining the efficiency of overhead ground wires are the shielding angle, the insulation level of the line, the pole ground resistances, and the distance between pole grounds. The shielding angle should not be greater than 30 to 40 degrees.[16] Calculated line flashover performance, based on the direct-stroke current data now available,[17] is shown in Figure 20. Part of the analysis was made analytically and part obtained with the model circuits. On the figure is also drawn a line corresponding to a probability of flashover of once every 140 years. This is the degree of protection being considered for strokes originating beyond the line arresters and, therefore, the degree of protection that should be provided by the ground wire. For the 500-foot ground wire where column *D* of Table IV shows a maximum permissible ground resistance of seven ohms, Figure 20 indicates a line-insulation level of 250 kv to be sufficient. If the length between pole grounds is only 125 feet, this is adequate for resistances up to about 15 ohms. When 1,000 feet of ground wire are required for resistances up to 25 ohms with 250-foot pole-ground intervals, or 50 ohms with 125-foot intervals, an insulation level of about 750 kv is indicated.

It should be emphasized that the grounding resistances in Table IV are not intended to indicate a precise set of rules for protection design. The individual values of maximum resistance for each machine-voltage class were tabulated to afford a basis for comparing the various protective schemes being considered. Both the 20,000-ampere arrester discharge and the 100 strokes per 100 miles of line for direct-stroke density are considered to be conservative amply to allow a variation of two to one in the permissible ground resistances. For more important installations in exposed regions, the tendency should be to approximate the listed values. When a comparison is made of the cost of the various elements of a line, it will be found usually that, if a ground wire is used, a 500-foot section is most economical. The shorter length of overhead ground wire, fewer pole grounds, and lower required line insulation usually will exceed greatly the required added cost of obtaining sufficiently low ground resistances. Probably, in most cases, it even will permit the installation of a buried counterpoise connecting the line-arrester ground with the machine ground. This will provide adequate protection for practically any grounding condition.

Machines Connected to Overhead Lines Through Cables

Effect of Sheath Grounding Conditions

There has been some question in the past as to the effect of various sheath grounding conditions on the voltages that will be transferred through cables. To study this, the tests illustrated in Figure 21 were made. The most significant are those of Figure 21a. At one end, the conductor and sheath were connected through a one-ohm resistor and the sheath grounded through a resistor varying from zero to 25 ohms. A constant current surge was introduced at this end for the various values of resistance, thereby applying a constant surge potential between the conductor and sheath, while successively higher sheath potentials resulted as the variable resistor was increased. These tests show that the potential applied to the sheath has little effect as long as the potential between conductor and sheath does not increase, and the machine end of the cable is grounded. It is the conductor-to-sheath potential that determines the voltage transferred through the cable. Figure 21b shows that, for any other condition of grounding, the transferred voltage is essentially determined by the line-to-ground potential introduced into the cable. When the arrester grounds are interconnected at the cable pothead, the transferred surge is determined by the voltage across the arrester and its short ground leads. Cables, therefore, provide a definite voltage-limiting benefit which is greatest for deion arresters with their low discharge voltages.

Cable Circuits Studied. Three principal types of cable conditions were studied for which typical solutions obtained with the equivalent circuits are shown in Figures 22 and 23. To determine the protection afforded with line arresters at the cable pothead only, the solutions of Figure 22 were obtained for a range of cable surge impedances and lengths, and various amounts of terminal capacity and lumped inductance at the line potheads. Studies also were made (Figure 23a) of the machine conditions produced by voltages maintained various distances out on an overhead line. This is typical of line flashover or of the discharge of line arresters out on the line. The effect of various amounts of cable in parallel with machines is shown in Figure 23b.

Protection With Deion Arresters at Cable Pothead Only. It can be seen readily from Figure 22 that the voltages permitted by valve arresters will produce too steep fronts at machines for the more common cable lengths, unless fairly large choke coils are provided. It was found that they should be of the order of 75 to 100 microhenrys for cables over 500 feet in length and as high as 300 for shorter cables. However, the deion arresters permit much lower values of inductance. In some cases none is required. Typical calculations of the voltage permitted by a deion arrester with a five-foot ground lead to the cable sheath are shown in Figures 24 and 25. For lengths less than about 200 feet, the cable itself provides little sloping and acts only as a voltage-limiting device. The location of the choke coils is not important. However, for lengths greater than 200 feet, sufficient increased wave sloping is provided by the cable capacitance to warrant placing them at the line end.

Table V lists rounded-off conservative values for the required choke-coil inductance when deion arresters are used only at the line pothead of cables connected to exposed overhead lines. These are much smaller than required when cables are not in the circuit. The largest needed is 50 microhenrys, if two standard capacitors are used for 6,900- and 11,500-volt ungrounded machines. Table V is based on the reasonable assumption that a direct stroke within 500 feet of the cable pothead will cause the deion arresters to discharge. Figure 26 illustrates calculations made to show that a stroke causing line flashover 500 feet away will not cause a severe machine-voltage front. Three flashover-voltage conditions marked *A*, *B*, and *C* were considered, causing either no discharge of the arresters or spark-over after various time intervals. The wave shape of the arrester voltage was obtained from the oscillograms of Figure 23a.

Use of Line Section Instead of Choke Coils. Past practice has been to treat machines connected to overhead lines through cables the same as without cables, except for the addition of arresters at the cable pothead; these are required for cable protection. If valve-type arresters are used at the cable pothead, it is still recommended that this procedure be followed. However, as shown in Table V, deion arresters at the cable pothead only are sufficient for certain cable lengths. If, for the other cases, a section of line (with additional arresters out on the line) is used instead of the choke coils, more inductance is required. This is because interconnection of these line arresters with the cable cannot be provided through short leads. However, the line-protection schemes found necessary for machines directly connected to overhead lines are not required. It was found that, for cables longer than 200 feet, a single additional set of arresters, 500 feet out on the line and having grounding resistances even as high as 50 to 75 ohms, provides good protection. This amount of line inductance is sufficient for any surge not discharging the pothead arresters. For more severe surges the pothead-arrester discharge current will be limited to a relatively low rate of rise by the line arresters. The type-*A* deion-arrester discharge voltages are much lower for currents having low rates of rise. The discharge conditions of Figure 15b are probably considerably more severe than any that could be propagated past the line arresters. Calculations, such as those of Figure 24, showed that good protection was provided for any cable longer than 200 feet, even with pothead-arrester discharge currents, such as that of Figure 15b. Cases with cables shorter than 200 feet should be treated as if the cables were not present with the addition of pothead arresters.

Cables in Parallel With Machines. Cables at the machine or bus terminals in parallel with the circuit into which a surge is propagating were found to produce practically the same sloping as an equivalent amount of lumped capacitance. As shown by Figure 23b, the superimposed oscillations are less severe for a larger number of shorter cables or for cables of lower surge impedance. However, if the cables provide a capacitance of 0.2 microfarad or more, the pulses will not be dangerously steep. Thus, if sufficient capacitance is provided in this way, surge-protective capacitors are not required. One condition which it is important to avoid is that illustrated by Figure 23a for a machine at point *B*. If capacitors are provided, they should be so placed that the surges will reach them before the machine, so that severe oscillations which can appear on the line side of the capacitors will not be impressed on the machine.

Machines Connected to Overhead Lines Through Transformers

The mechanism by which surges are transferred through transformers has been treated in detail elsewhere.[18,19] It will be considered here only to the extent of establishing a basis for machine protection. Since the transformer-leakage inductance is always sufficient for wave-sloping purposes, it is not necessary to provide arresters out on the line. Station-type arresters, however, should be provided on the line side of the transformer bank connected to very low station grounds and preferably interconnected to the machine grounds. The surge-voltage conditions are determined by the station arresters. Average data on the discharge-voltage characteristics of the station-type arresters commonly used for transformer protection are given in reference 20. For 33 kv or higher, the arrester discharge voltage is sufficiently high compared with the short-duration lead-inductive drops which might occur, so that only the discharge voltage need be considered. It can be represented as a square voltage wave. This, of course, assumes that low station ground resistance or interconnection with the machine grounds is provided. For a current of 20,000 amperes, the arrester discharge voltage is about 2.5 times the crest-rated line-to-line voltage when 80 per cent arresters are used on grounded systems. For ungrounded systems using 100 per cent arresters it is about 3.1. Even for abnormally high discharge currents of 50,000 amperes, these values are increased only to 2.7 and 3.4, respectively. When a steep-front surge is applied to a transformer bank, voltage can be transferred electrostatically through the distributed capacitance between windings and also electromagnetically. The voltages transferred in these two ways can be considered separately.

ELECTROSTATIC COMPONENT

The electrostatic component is dependent on not only the total capacitances between windings and to ground but also their distribution along the windings. In general, therefore, it is not practical to consider individual cases. A study was made of a representative group of shell- and core-type transformers, and this was co-ordinated with the tests reported by Bellaschi.[19] With the secondary winding of transformer banks open or connected to impedances of several-hundred ohms, the electrostatic component can produce surges of severe magnitudes and fronts that usually range from 0.5 to three microseconds. However, in any transformer bank it can be reduced sufficiently for machine-protection purposes if resistances of 50 ohms or less or capacitances of 0.005 microfarad or more are connected across the secondary terminals.

Since the total capacity of machine windings usually ranges between 0.02 and 0.6 microfarad, it might be thought that the machine itself would eliminate this component. However, actual tests made by applying surges to transformer banks connected to the 100-kva machine described show that this is not so. The transformers used had lower capacities compared with capacities of the machine than is usually typical. However, tests such as that of Figure 27 show that the machine acts only as a surge impedance or resistance and has little effect on the electrostatic component. Except when surge-protection capacitors are applied, the only circuit elements commonly present to eliminate the electrostatic component are cables. The data of Figure 10 can be used to determine the capacitance provided by these. A 50-foot length is all that is required for most cables to supply the necessary 0.005 microfarad. Thus, if such cables are connected either between the machine and transformer or in parallel with the machine, special surge-protection capacitors are not required for the electrostatic component.

Electromagnetic Component

With sufficient capacitance in the circuit to eliminate the electrostatic component, the electromagnetic component can be determined quite accurately from the equivalent circuit and solutions of Figure 28. A complete tabulation of transformer-leakage reactances (including autotransformers) is given in reference 21. Three-winding transformers can be treated accurately in terms of their equivalent leakage-reactance circuit.[21] However, a safe approximation results from considering the tertiary windings open-circuited and treating them as two-winding transformers. The constant K, determining the effective applied surge voltage for different bank connections, is discussed in detail in reference 18. It gives the highest machine voltages which can be produced. This is usually from surges on one or two phases. An example of the use of Figure 28 in calculating machine lightning-surge voltages is given in Figure 29. After M is evaluated, the shape of the voltage curve can be determined from the curves of Figure 28. The proper time scale is supplied from T and the magnitude from NKE_a. For this case, the cable provides sufficient capacitance to limit safely surges induced both electrostatically and electromagnetically.

Examination of the equations for T and M in Figure 28 shows that sloping is increased by increased values of capacitance, but that overshooting of the voltage is also increased. Thus, there is a limited range of capacitance for which machine arresters and capacitors are not required. If a calculation such as that of Figure 29 should show the need of machine arresters to limit the machine voltage, capacitors also should be used to prevent steep-front surges resulting from a sudden drop in the machine-arrester voltage when it discharges. Likewise, if the need for surge capacitors is indicated to provide adequate wave sloping (or to prevent electrostatically induced surges), machine arresters also should be used, because the capacitors usually will increase the overshooting of voltage to a dangerous value, even for the lower range of machine surge impedances. This is true unless resistance were placed in series with the capacitors. For capacitances of 0.25 microfarad or more the machine surge impedance need not be represented and the solution, for this case is given by Figure 16b. Calculations of the series resistance necessary to provide adequate damping show that it usually must exceed 50 ohms. If no other capacitance is available in the circuit for suppressing the electrostatic component, a resistance in series with the surge capacitors appreciably in excess of 50 ohms might permit this component to be severe. In general, the use of the capacitors and machine arresters is to be preferred.

Ungrounded Machines. Except for the case of an ungrounded machine connected to a wye–wye bank with both neutrals grounded, no more severe voltage conditions can be set up at the machine neutral than at its terminals. For surges produced on one or two phases of the primary winding, all bank connections, except the grounded wye–wye, produce surges of opposing polarities at the machine terminals, so that they tend to cancel at the machine neutral. For surges appearing simultaneously on all three phases of the primary winding, no appreciable voltages are transferred electromagnetically to the machine. Thus, no extra protection is required. For grounded wye–wye banks, machine arresters are always required, and, thus, capacitors should be added also. In most cases the addition of the standard capacitors provides fronts in excess of 30 or 40 microseconds, so that severe neutral voltage conditions are not likely.

Quick Method of Determining Need for Machine Protection. In the summary is given a quick method for determining the need for machine arresters and capacitors. Two steps are listed for considering electromagnetically induced surges. Step 1 pertains to adequate sloping, and the relationship is obtained from the equation for T in Figure 28. It provides a value of 12 microseconds for $0.5T$. Step 2, pertaining to adequate damping of the induced voltage, was obtained from the equation for M. It is based on the following conservative assumptions:

1. The damping is provided by only one machine.

2. Effective surge impedances ranging from 500 ohms for 2,400-volt machines to 1,000 ohms for 13,800-volt machines are assumed to be conservatively high for hydrogenerators and other slower-speed machines. A resistance of 250 to 500 ohms is assumed for turbogenerators and other machines with speeds above 1,800 rpm.

3. The voltages permitted by the station arresters are assumed to be 2.5 and 3.1 times crest line-to-line normal line voltage for 80 and 100 per cent arresters, respectively.

4. The machine insulation strength is considered to be only that given by the standard test voltages of Table II.

Magnitude of Machine-Arrester Discharge Currents

Best protection is afforded when the machine-arrester discharge currents are limited to 2,000 amperes or less, since their discharge voltages may exceed the safe protective levels for higher currents. A study, therefore, was made of this for each protection method recommended here. Using a model arrester having gap breakdown and discharge voltage characteristics scaled down by a factor of 10, the currents were measured in the equivalent circuits being studied. In Figure 30 are shown two of the solutions obtained together with the voltage characteristics of an actual machine arrester. In all cases, it was found that the currents were limited to safe values which were appreciably less than permitted by the former recommendations of 1,500 feet of line and one set of arresters for machines connected directly to overhead lines. This is illustrated in Figure 30.

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Electric-Circuit Fault-Protective Principles as Applied to D-C Aircraft Systems

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AIRCRAFT d-c electric systems are being extended constantly in responsibility and physical size. The assignment of more important tasks to the electric system emphasizes the need for the highest order of reliability of power supply, particularly in military craft exposed to unusual hazards. The increase in electric plant capacity increases the concentration of electric power which may be unleashed with damaging effect in the event of electric-circuit fault.

An electric-circuit fault results from an unintentional connection between energized conductors of different potentials or between an energized conductor and the ship structure or metallic enclosure connected thereto. The location of a particular electric fault is, of course, quite unpredictable and may appear at any point along the energized conductor system or machine internal windings. Through the by-pass circuit provided by the electric fault, excessively high current may flow which may jeopardize continued operation of the entire system, as well as constitute a serious hazard to equipment and personnel in the immediate vicinity of the fault.

It is the purpose of this paper to provide a clear understanding of system fault-protective measures as applicable to current d-c aircraft systems. Many of the principles herein described may be applied equally well to a-c aircraft systems. It will be well at this point to distinguish between equipment thermal protection and system fault protection.

Thermal Versus Fault Protection

Thermal protection aims to prevent electrical failure by interrupting the supply of power when the maximum safe operating temperature is reached. Temperature measurement may be made by embedded temperature detectors or determined from previous time–current history. The presence of thermal protection may eliminate or minimize needless burnouts of circuits or equipment. On the other hand, in aircraft service under combat conditions, there are certain functions which are extremely important, and additional combat hazards resulting from the inability of such important machines to operate may more than offset the hazards encountered by continuing the operation of these machines above maximum safe temperatures. Under these circumstances, the ability to override normal thermal protection seems quite sensible. Except during such hectic circumstances, normal properly applied thermal protection will pay dividends in the form of increased useful life. If, in the course of driving a machine above its normal thermal operating limit, a failure is induced, its usefulness abruptly ceases at that point.

In contrast to this is fault or system protection which aims to interrupt promptly the flow of power following the occurrence of electrical failure. The purposes of interruption are:

1. To minimize the energy liberated at the point of fault, thus minimizing fire hazard.
2. To avoid burning up electric conductors.
3. To minimize damage to immediately adjacent electric conductors and additional fire hazard.
4. To divorce the faulted circuit from the main electric system in order that the latter may continue to operate in a normal manner.

To permit fault protection to be overridden is most hazardous and easily may result in a destructive fire, mechanical disruption of electric-system elements in the vicinity of the fault, and/or complete collapse of the main electric system. It may be noted that the flow of 5,000 amperes into a ten-volt fault circuit represents the liberation of power in the form of heat at the rate of 50 kw. To sustain such high-current levels into a fault produces no useful result whatsoever. The overriding of fault protection is distinctly different and not to be confused with permissible reclosure using a trip-free circuit breaker which immediately will operate to interrupt the circuit if abnormally high-current flow is again established.

In many instances it may be possible to combine thermal and fault protection in a common mechanism. However, the two functions shall continue to retain their individual significance. Although moderate overcurrents may be permitted to continue for a substantial time interval before significant damage results, current flow far in excess of normal value is unquestionably the result of a fault, and no time should be lost in severing the faulted section from the system.

Obviously, it is important that any protective system correctly appraise operating conditions and function to interrupt promptly a circuit element involved in fault, yet positively refrain from interrupting in the absence of fault. Furthermore, only protective devices immediately adjacent to the fault should operate, thus limiting service area interruption to the absolute mini-

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